



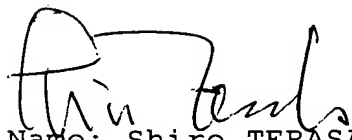
VERIFICATION

The undersigned, of the below address, hereby certifies that he/she well knows both the English and Japanese languages, and that the attached is an accurate English translation of the Japanese Patent application filed on September 9, 2002 under No. P2002-263199.

The undersigned declares further that all statements made herein of his/her own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issuing thereon.

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[Document Name] Specification

[Title of the Invention]

EXCHANGE-COUPLED FILM, SPIN VALVE FILM, THIN FILM MAGNETIC
HEAD, MAGNETIC HEAD APPARATUS, AND MAGNETIC
5 RECORDING/REPRODUCING APPARATUS

[Claims]

[Claim 1] An exchange-coupled film in which an
antiferromagnetic layer and a ferromagnetic layer sandwich
are stacked and in which a direction of magnetization of
10 the ferromagnetic layer sandwich is pinned,

wherein said ferromagnetic layer sandwich comprises
a first ferromagnetic layer containing a ferromagnetic
material of the body-centered cubic structure, and a pair
of second ferromagnetic layers containing a ferromagnetic
15 material of the face-centered cubic structure and formed
on respective sides of the first ferromagnetic layer; and

wherein said antiferromagnetic layer contains a
disordered alloy and is kept in contact with one of said
second ferromagnetic layers.

[Claim 2] The exchange-coupled film according to Claim
1, wherein the ferromagnetic layer sandwich further comprises
a third ferromagnetic layer placed through a nonmagnetic
intermediate layer on the opposite side to the
antiferromagnetic layer with the other second ferromagnetic
25 layer in between.

[Claim 3] A spin valve film comprising the

exchange-coupled film as set forth in Claim 1 or 2; a
nonmagnetic, conductive layer laid on the ferromagnetic layer
sandwich of the exchange-coupled film; and a free layer laid
on the nonmagnetic, conductive layer and containing a
5 ferromagnetic material.

[Claim 4] A thin film magnetic head comprising the spin
valve film as set forth in Claim 3, and a pair of magnetic
shield layers placed at positions where the spin valve film
is sandwiched therebetween from both sides in a stack
10 direction of the spin valve film, and containing a soft
magnetic material.

[Claim 5] The thin film magnetic head according to Claim
4, comprising a pair of electrode layers electrically
connected to the spin valve film and adapted for allowing
15 an electric current to flow parallel to a film surface of
the spin valve film.

[Claim 6] The thin film magnetic head according to Claim
4, comprising a pair of electrode layers electrically
connected to the spin valve film and adapted for allowing
20 an electric current to flow perpendicular to a film surface
of the spin valve film.

[Claim 7] A magnetic head apparatus comprising the thin
film magnetic head as set forth in anyone of Claims 4 to
6; and a head supporting device for supporting the thin film
25 magnetic head.

[Claim 8] A magnetic recording/reproducing apparatus

comprising the magnetic head apparatus as set forth in Claim 7; and a magnetic recording medium for implementing magnetic recording/reproduction in collaboration with the thin film magnetic head of the magnetic head apparatus.

5 [Detailed Description of the Invention]

[0001]

[Technical Field to which the Invention Pertains]

The present invention relates to an exchange-coupled film including ferromagnetic layers and an antiferromagnetic layer, a spin valve film using it, a thin film magnetic head, a magnetic head apparatus, and a magnetic recording/reproducing apparatus.

[0002]

[Prior Art]

15 The known thin film magnetic heads include thin film magnetic heads provided with a spin valve film in which an antiferromagnetic layer, a ferromagnetic layer, a nonmagnetic, conductive layer, and a ferromagnetic layer are successively stacked (e.g., patent document1 and 2).

20 In such thin film magnetic heads a direction of magnetization of the ferromagnetic layer in contact with the antiferromagnetic layer is pinned by exchange coupling between the antiferromagnetic layer and the ferromagnetic layer. In order to improve the reliability of the thin film

25 magnetic heads, exchange coupling energy of the exchange-coupled film including the antiferromagnetic layer

and the ferromagnetic layer exchange coupled with the antiferromagnetic layer needs to be sufficiently high.

[0003]

The known exchange-coupled films include the exchange-coupled films using a PtMn layer and a CoFe layer (e.g., patent document 3), the exchange-coupled films using an NiMn layer and a CoFe layer (e.g., patent document 4 and 5), the exchange-coupled films using an IrMn layer and a CoFe layer (e.g., patent document 6), the exchange-coupled films using an RuRhMn layer and an NiFe layer (e.g., patent document 7), and so on.

[0004]

There are other known exchange-coupled films in which the ferromagnetic layer thereof is comprised of a ferromagnetic layer sandwich of trilayered structure consisting of a ferromagnetic layer/a nonmagnetic metal intermediate layer/a ferromagnetic layer, so as to antiferromagnetically exchange couple the two ferromagnetic layers with each other, thereby achieving an effective increase of exchange coupling force from the antiferromagnetic layer to the ferromagnetic layer sandwich (e.g., patent document 8).

[0005]

Furthermore, disclosed is a method of interposing a matching ferromagnetic layer between the antiferromagnetic layer and the ferromagnetic layer in the exchange-coupled

film to enhance exchange coupling (e.g., patent document 9).

[0006]

[patent document1]

5 Japanese examined Patent Publication No. 08-21166

[patent document2]

Japanese Patent Application Laid-Open No. 06-236527

[patent document3]

Japanese Patent Application Laid-Open No. 09-147325

10 [patent document4]

Japanese Patent Applications Laid-Open No. 09-63021

[patent document5]

Japanese Patent Applications Laid-Open No. 09-50611

[patent document6]

15 Japanese Patent Application Laid-Open No. 09-148132

[patent document7]

Japanese Patent Application Laid-Open No. 10-242544

[patent document8]

Japanese Patent Application Laid-Open No. 2000-137906

20 [patent document9]

Japanese Patent Application Laid-Open No. 09-82524

[Problem to be Solved by the Invention]

Concerning the thin film magnetic heads, there are demands for readout from magnetic recording media in which information is recorded in higher density, and, in order to meet the demands, it is necessary to achieve so-called

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gap narrowing to narrow the gap between a pair of magnetic shield layers placed on the both sides of the spin valve film in the thin film magnetic head.

[0007]

5 It is difficult to further decrease the currently achieved thicknesses of insulating layers among the layers placed between the magnetic shield layers, and it is thus necessary to decrease the thickness of the spin valve film. In order to make the spin valve film thinner, it is then
10 effective to decrease the thickness of the antiferromagnetic layer, which has the thickness larger than those of the other layers in the spin valve film. However, a further decrease of the current thickness of the antiferromagnetic layer in the conventional exchange-coupled films will result in posing
15 a problem of failure in yielding sufficient exchange coupling energy.

[0008]

 The present invention has been accomplished in view of the above problem and an object of the invention is to
20 provide an exchange-coupled film that can be made thinner than before and that yields sufficient exchange coupling energy, a spin valve film using it, a thin film magnetic head, a magnetic head apparatus, and a magnetic recording/reproducing apparatus.

25 [0009]

[Means for Solving the Problem]

The Inventors conducted elaborate research, found that sufficient exchange coupling energy was yielded even with decrease in the thickness of the antiferromagnetic layer from that before, by the exchange-coupled film adopting a ferromagnetic layer sandwich comprising a first ferromagnetic layer containing a ferromagnetic material of the body-centered cubic structure; and a pair of second ferromagnetic layers containing a ferromagnetic material of the face-centered cubic structure and laid on respective sides of the first ferromagnetic layer, and an antiferromagnetic layer containing a disordered alloy and kept in contact with one of the second ferromagnetic layers, and thereby completed the present invention.

[0010]

An exchange-coupled film according to the present invention is an exchange-coupled film in which an antiferromagnetic layer and a ferromagnetic layer sandwich are stacked and in which a direction of magnetization of the ferromagnetic layer sandwich is pinned, wherein the ferromagnetic layer sandwich comprises a first ferromagnetic layer containing a ferromagnetic material of the body-centered cubic structure, and a pair of second ferromagnetic layers containing a ferromagnetic material of the face-centered cubic structure and formed on respective sides of the first ferromagnetic layer, and wherein the antiferromagnetic layer contains a disordered alloy and is

kept in contact with one of the second ferromagnetic layers.

[0011]

In the exchange-coupled film of the present invention, the direction of magnetization of the ferromagnetic layer sandwich is pinned by exchange coupling with the antiferromagnetic layer. At this time, sufficient exchange coupling energy is yielded even in a smaller thickness of the antiferromagnetic layer than before, so as to adequately pin the direction of magnetization of the ferromagnetic layer sandwich; therefore, the thickness of the exchange-coupled film can be made smaller than before.

[0012]

In the above exchange-coupled film, preferably, the ferromagnetic layer sandwich further comprises a third ferromagnetic layer placed through a nonmagnetic intermediate layer on the opposite side to the antiferromagnetic layer with the other second ferromagnetic layer in between.

[0013]

In this configuration, the third ferromagnetic layer is antiferromagnetically exchange coupled through the nonmagnetic intermediate layer with the first ferromagnetic layer and the pair of second ferromagnetic layers on the both sides of the first ferromagnetic layer in the ferromagnetic layer sandwich, which achieves an effective increase of the force of the antiferromagnetic layer's

pinning the direction of magnetization of the ferromagnetic layer sandwich. Since a closed magnetic field is created, leakage is reduced of the magnetic field from the ferromagnetic layer structure.

5 [0014]

A spin valve film according to the present invention comprises the foregoing exchange-coupled film; a nonmagnetic, conductive layer laid on the ferromagnetic layer sandwich of the exchange-coupled film; and a free layer laid
10 on the nonmagnetic, conductive layer and containing a ferromagnetic material.

[0015]

Since the spin valve film of the present invention adopts the aforementioned exchange-coupled film, it can
15 adequately pin the direction of magnetization of the ferromagnetic layer sandwich and decrease the thickness of the spin valve film.

[0016]

A thin film magnetic head according to the present
20 invention comprises the above-stated spin valve film; and a pair of magnetic shield layers placed at positions where the spin valve film is sandwiched therebetween from both sides in a stack direction of the spin valve film, and containing a soft magnetic material.

25 [0017]

Since the thin film magnetic head of the present

invention has the aforementioned exchange-coupled film, the thickness of the spin valve film can be decreased. For this reason, the gap can be narrowed between the pair of magnetic shield layers on the both sides of the spin valve film and it becomes feasible to detect the leakage field from media in which magnetic information is recorded in higher density.

[0018]

The above thin film magnetic head may comprise a pair of electrode layers electrically connected to the spin valve film and adapted for allowing an electric current to flow parallel to a film surface of the spin valve film.

[0019]

In the so-called CIP type thin film magnetic head as described above, the decrease in the thickness of the antiferromagnetic layer because of the inclusion of the aforementioned exchange-coupled film results in decreasing a shunt ratio of an electric current flowing in the antiferromagnetic layer among electric currents flowing in the spin valve film and thereby increasing the MR ratio of the thin film magnetic head.

[0020]

The above thin film magnetic head may comprise a pair of electrode layers electrically connected to the spin valve film and adapted for allowing an electric current to flow perpendicular to a film surface of the spin valve film.

[0021]

In the so-called CPP type thin film magnetic head as described above, the decrease in the thickness of the antiferromagnetic layer because of the inclusion of the aforementioned exchange-coupled film results in decreasing the resistance during flow of an electric current through the antiferromagnetic layer in the spin valve film and thereby increasing the MR ratio of the thin film magnetic head.

[0022]

A magnetic head apparatus according to the present invention comprises the above-stated thin film magnetic head, and a head supporting device for supporting the thin film magnetic head.

[0023]

A magnetic recording/reproducing apparatus according to the present invention comprises the above-stated magnetic head apparatus and a magnetic recording medium for implementing magnetic recording/reproduction in collaboration with the thin film magnetic head of the magnetic head apparatus.

[0024]

Since the above magnetic head apparatus and magnetic recording/reproducing apparatus are provided with the aforementioned thin film magnetic head, it becomes feasible to increase the recording density.

[0025]

[Embodiments of the Invention]

The preferred embodiments of the present invention will be described below in detail with reference to the accompanying drawings. In the description of the drawings, identical or equivalent elements will be denoted by the same reference symbols, without redundant description thereof.

[0026]

First, the exchange-coupled film according to an embodiment of the present invention will be described with reference to Fig. 1. The exchange-coupled film 100 according to the present embodiment has an antiferromagnetic layer 7 of disordered alloy structure, and a ferromagnetic layer sandwich 41 stacked on the antiferromagnetic layer 7.

[0027]

The ferromagnetic layer sandwich 41 consists of a first ferromagnetic layer 13 containing a ferromagnetic material of the body-centered cubic structure (BCC), and a pair of second ferromagnetic layer 11A and second ferromagnetic layer 11B containing a ferromagnetic material of the face-centered cubic structure (FCC) and formed on respective sides of the first ferromagnetic layer 13. The second ferromagnetic layer 11A is in contact with the antiferromagnetic layer 7.

[0028]

The first ferromagnetic layer 13 is preferably made of Fe or an iron-rich alloy of the body-centered cubic structure. The iron-rich alloy can be selected, for example,

from Fe₉₅Ta containing iron 95%, Fe₉₀Co containing iron 90%,
Fe₅₀Co containing iron 50%, and so on.

[0029]

The second ferromagnetic layers 11A and 11B can be made
of a ferromagnetic material of the face-centered cubic
structure; for example, one selected from Co, Co₉₀Fe
containing cobalt 90%, Ni₈₀Fe containing nickel 80%, and so
on.

[0030]

The antiferromagnetic layer 7 is an antiferromagnetic
material of the disordered alloy structure; for example,
it can be an alloy of „-Mn base structure and is preferably
one of alloys such as IrMn, RuRhMn, FeMn, RuMn, and so on.
Compositions of these alloys can be, for example, IrMn₈₀,
FeMn₈₀, RuRhMn₈₀, RuMn₈₀, and so on.

[0031]

The antiferromagnetic layer 7 is formed so as to come
into contact with anyone of the second ferromagnetic layers
11A in the ferromagnetic layer sandwich 41. The magnetic
field of exchange-coupling is induced on the interface
between the second ferromagnetic layers 11A and the
antiferromagnetic layer 7, accordingly, the direction of
magnetization of the ferromagnetic layer sandwich 41 is
pinned.

[0032]

The exchange-coupled film may be of the so-called

synthetic structure in which a third ferromagnetic layer is laid through a nonmagnetic layer on the second ferromagnetic layer 11B so that the third ferromagnetic layer is antiferromagnetically exchange coupled through the nonmagnetic layer with the first ferromagnetic layer 13 and the second ferromagnetic layers 11A, 11B. In this case, the antiferromagnetic layer 7 effectively increases its pinning force for pinning the direction of magnetization of the ferromagnetic layer sandwich 41.

[0033]

The exchange-coupled film described above can be readily formed by depositing the antiferromagnetic layer 7, second ferromagnetic layer 11A, first ferromagnetic layer 13, and second ferromagnetic layer 11B on an unrepresented substrate in this order or in the reverse order by sputtering or the like.

[0034]

In the exchange-coupled film of the present embodiment, sufficiently high exchange coupling energy is yielded even in smaller thickness of the antiferromagnetic layer than before, which permits decrease in the thickness of the exchange-coupled film.

[0035]

There are no specific restrictions on the thicknesses of the first ferromagnetic layer 13, second ferromagnetic layer 11A, and second ferromagnetic layer 11B, but it is

preferable to set the thickness of the first ferromagnetic layer 13 in the range of approximately 0.5 to 3 nm and set the thicknesses of the second ferromagnetic layers 11A, 11B in the range of approximately 0.5 to 1.5 nm. There are no specific restrictions on the thickness of the antiferromagnetic layer 7, either, but it is preferable to set the thickness in the range of approximately 5 to 10 nm.

[0036]

We checked the characteristics of exchange coupling energy and others of exchange-coupled films according to the present embodiment.

[0037]

(Examples 1-4)

Exchange-coupled films were formed as follows: Ta was deposited as an under layer in the thickness of 5 nm on a substrate of AlTiC or the like having an under film of Al_2O_3 , thereafter the second ferromagnetic layer A of the face-centered cubic structure, the first ferromagnetic layer of the body-centered cubic structure, and the second ferromagnetic layer B of the face-centered cubic structure were successively deposited to form a ferromagnetic layer sandwich, the antiferromagnetic layer of a disordered alloy was further formed on the second ferromagnetic layer B, and Ta was further deposited as a capping layer in the thickness of 5 nm thereon. Each of the layers was made by sputtering.

[0038]

As presented in the table of Fig. 2, the film composition of the ferromagnetic layer sandwich in each of Examples was the second ferromagnetic layer A/first ferromagnetic layer/second ferromagnetic layer B: Co_{90}Fe 0.5 nm thick, Fe_{95}Ta 3 nm thick, and Co_{90}Fe 0.5 nm thick in the order named. The antiferromagnetic layer was made of $\text{Ir}_{20}\text{Mn}_{80}$ and in the thickness being one of 10, 9, 7, and 5 nm in Examples 1 to 4, respectively. In Fig. 2, the second ferromagnetic layer B was in contact with the antiferromagnetic layer.

[0039]

(Examples 5-7)

Exchange-coupled films of Examples 5-7 were made in the same manner as in Example 1 except that the antiferromagnetic layer was made of RuRhMn_{80} of another disordered alloy, instead of IrMn , and in the thickness being one of 11, 9, and 7 nm in Examples 5-7, respectively.

[0040]

(Example 8)

An exchange-coupled film of Example 8 was made in the same manner as in Example 4 except that the film composition of the ferromagnetic layer sandwich was the second ferromagnetic layer A/first ferromagnetic layer/second ferromagnetic layer B: Co_{90}Fe 1 nm thick, Fe_{50}Co 2 nm thick, and Co_{90}Fe 1 nm thick in the order named.

[0041]

(Comparative Examples 1-6)

Exchange-coupled films of Comparative Example 1 and Comparative Example 2 were made in the same manner as in Example 1 and in Example 4, respectively, except that the ferromagnetic layer sandwich was a single layer of Co_{90}Fe 3 nm thick. Exchange-coupled films of Comparative Example 3 and Comparative Example 4 were made in the same manner as in Example 1 and Example 4, respectively, except that the ferromagnetic layer sandwich was a single layer of Co_{90}Fe 2 nm thick.

[0042]

(Comparative Example 5)

An exchange-coupled film of Comparative Example 5 was made in the same manner as in Example 1 except that the ferromagnetic layer sandwich was one consisting of two layers of Co_{90}Fe 2 nm thick and Fe_{95}Ta 2 nm thick and the layer of $\text{Ir}_{20}\text{Mn}_{80}$ was laid on the FeTa layer.

[0043]

(Comparative Examples 6-8)

Exchange-coupled films of Comparative Examples 6-8 were made in the same manner as in Example 1 except that a layer of PtMn being an ordered alloy was laid as an antiferromagnetic layer in the thickness being one of 15, 13, and 10 nm in Comparative Examples 6-8, respectively.

[0044]

(Comparative Examples 9, 10)

Exchange-coupled films of Comparative Examples 9, 10

were made in structure in which the ferromagnetic layer sandwich was a single layer of Co_{90}Fe 3 nm thick and in which the antiferromagnetic layer was made of PtMn being an ordered alloy and in the thickness being one of 15 and 5 nm in Comparative Examples 9 and 10, respectively.

[0045]

(Reference Example 1)

An exchange-coupled film was made in structure in which the ferromagnetic layer sandwich was a stack of two layers of Co_{90}Fe 2 nm thick and Fe_{50}Co 2 nm thick and in which a layer of IrMn_{80} was laid on the Fe_{50}Co layer.

[0046]

A magnetization curve was measured in the direction of the magnetization easy axis for each of the exchange-coupled films obtained as described above. Fig. 3 shows a typical example of the magnetization curves obtained. The magnetization curve of the ferromagnetic layer sandwich had a shift from the origin 0 because of the exchange coupling with the antiferromagnetic layer, the amount of this shift was obtained as exchange coupling field H_{ex} , and the lateral width H_{cp} of the hysteresis loop was also obtained. The exchange coupling energy J_k of each exchange-coupled film was calculated based on the exchange coupling field H_{ex} . The exchange coupling energy was estimated by $J_k [\text{J/m}^2] = (H_{\text{ex}}[\text{A/m}]) \times (M_{\text{s}0}[\text{Wb/m}^2]) \times (t_{\text{a}}[\text{m}])$, using CoFe reduced thickness t_{a} obtained by converting the

thickness of the ferromagnetic layer sandwich to that of the Co_{90}Fe layer with saturation magnetization M_{s0} .

[0047]

The results of these are given in the table of Fig. 2. For calculating the CoFe reduced thickness t_a in the calculation of exchange coupling energy J_k , the saturation magnetizations M_{s0} adopted were as follows: 1.9 Wb/m^2 as the saturation magnetization of $\text{Co}_{90}\text{Fe}_{10}$, 1.48 Wb/m^2 as the saturation magnetization of Fe_{95}Ta , and 2.18 Wb/m^2 as the saturation magnetization of $\text{Fe}_{50}\text{Co}_{50}$.

[0048]

It is seen that the exchange-coupled films using the ferromagnetic layer sandwich with the pair of Co_{90}Fe layers of the face-centered cubic structure on the both sides of the FeTa layer of the body-centered cubic structure, and the layer of IrMn being the disordered alloy as an antiferromagnetic layer yield the exchange coupling energy J_k of not less than 287 „J/m^2 where the antiferromagnetic layer has the thickness in the range of 10-5 nm, as in Examples 1-4.

[0049]

It is also seen that the exchange-coupled films using the same ferromagnetic layer sandwich as in Examples 1-4 and the antiferromagnetic layer of RuRhMn of the disordered alloy also yield the high exchange coupling energy J_k of not less than 234 „J/m^2 where the antiferromagnetic layer

has the thickness in the range of 7-11 nm, as in Examples 5-7.

[0050]

Furthermore, as in Example 8, the exchange-coupled film comprised of the ferromagnetic layer sandwich with the pair of Co_{90}Fe layers of the face-centered cubic structure on the both sides of the Fe_{50}Co layer of the body-centered cubic structure, and the antiferromagnetic layer of IrMn also yields the high exchange coupling energy of 545 „J/m^2 where the antiferromagnetic layer has the thickness of 5 nm.

[0051]

On the other hand, the conventionally known exchange-coupled films using the single layer of Co_{90}Fe as the ferromagnetic layer sandwich and IrMn as the antiferromagnetic layer failed to yield the exchange coupling energy J_k over 184 „J/m^2 where the antiferromagnetic layer had the thickness in the range of 5-10 nm, as in Comparative Examples 1-4.

[0052]

The exchange-coupled film using IrMn as the antiferromagnetic layer and the ferromagnetic layer sandwich of two layers of $\text{Co}_{90}\text{Fe}/\text{FeTa}$ as the ferromagnetic layer sandwich also failed to yield sufficient exchange coupling energy J_k , as in Comparative Example 5.

[0053]

In the case of the exchange-coupled films of the

composition consisting of the ferromagnetic layer sandwich of Example 1 and PtMn being the ordered alloy, the exchange coupling energy J_k dominantly decreases with decrease in the thickness of the antiferromagnetic layer, and the exchange coupling energy J_k becomes as low as approximately 105 $\mu\text{J}/\text{m}^2$ and insufficient where the antiferromagnetic layer has the thickness of 10 nm, as in Comparative Examples 6-8.

[0054]

In addition, in the case of the exchange-coupled films of the conventional composition consisting of PtMn of the ordered alloy and Co_{90}Fe , as seen in Comparative Examples 9, 10, the exchange-coupled film demonstrates the sufficient exchange coupling energy of 365 $\mu\text{J}/\text{m}^2$ where the antiferromagnetic layer has the thickness of approximately 15 nm, whereas the exchange coupling energy decreases to approximately 41.6 $\mu\text{J}/\text{m}^2$ and is thus insufficient where the thickness of PtMn as the antiferromagnetic layer becomes as thin as about 5 nm.

[0055]

As evidenced by the above data, it was verified that the exchange-coupled films having the sufficient exchange coupling energy even with the antiferromagnetic layer as thin as approximately 10 nm or less were substantiated by the exchange-coupled films consisting of the combination of the ferromagnetic layer sandwich having the pair of ferromagnetic layers containing the ferromagnetic material

of the face-centered cubic structure on the both sides of the first ferromagnetic layer containing the ferromagnetic material of the body-centered cubic structure, with the antiferromagnetic layer of the disordered alloy.

5 [0056]

As seen from Reference Example 1, the $\text{Co}_{90}\text{Fe}/\text{Fe}_{50}\text{Co}/\text{IrMn}$ -based exchange-coupled film also demonstrates the high exchange coupling energy J_k of 339 J/m^2 , as compared with Comparative Example 1 and others. However, the exchange coupling energy J_k becomes higher when the Fe_{50}Co layer of the body-centered cubic structure is placed between the Co_{90}Fe layers of the face-centered cubic structure, as in the case of the $\text{Co}_{90}\text{Fe}/\text{Fe}_{50}\text{Co}/\text{Co}_{90}\text{Fe}/\text{IrMn}$ -based exchange-coupled film as in Example 8.

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[0057]

The lateral widths H_{cp} of the hysteresis loops of the magnetic curves fall in the range of approximately 9.2 to 17 kA/m in Examples 1-8, which are not a cause for concern.

20 [0058]

Next, changes of the exchange coupling energy and others were measured with change in the thicknesses of the three ferromagnetic layers forming the ferromagnetic layer sandwich, in the case of the exchange-coupled film of the composition of $\text{Co}_{90}\text{Fe}/\text{Fe}_{95}\text{Ta}/\text{Co}_{90}\text{Fe}/\text{IrMn}_{80}$ as in Example 1 and in the case of the exchange-coupled film of the composition

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of $\text{Co}_{90}\text{Fe}/\text{Fe}_{50}\text{Co}/\text{Co}_{90}\text{Fe}/\text{IrMn}_{80}$ as in Example 8.

[0059]

(Examples 9-15)

The exchange-coupled films of Examples 9-15 were made
5 in the same manner as in Example 1 except that the thicknesses
of the respective layers of $\text{Co}_{90}\text{Fe}/\text{Fe}_{95}\text{Ta}/\text{Co}_{90}\text{Fe}$ in the
ferromagnetic layer sandwich were changed as described in
the table of Fig. 4.

[0060]

10 (Examples 16-21)

The exchange-coupled films of Examples 16-21 were made
in the same manner as in Example 8 except that the thicknesses
of the respective layers of $\text{Co}_{90}\text{Fe}/\text{Fe}_{50}\text{Co}/\text{Co}_{90}\text{Fe}$ in the
ferromagnetic layer sandwich were changed as described in
15 the table of Fig. 5.

[0061]

As seen from Examples 9-11 (Fig. 4), the
 $\text{Co}_{90}\text{Fe}/\text{Fe}_{95}\text{Ta}/\text{Co}_{90}\text{Fe}/\text{IrMn}$ -based exchange-coupled films
demonstrated a slight increase of the exchange coupling
20 energy J_k as the second ferromagnetic layer B in contact
with the antiferromagnetic layer increased its thickness.
However, when consideration is given to the increase rate
being small and to an output drop due to shunt loss of electric
current, the thickness of the second ferromagnetic layer
25 B is considered to be preferably determined in the range
of approximately 0.5 to 1.0 nm. On the other hand, as seen

from Examples 8, 16, and 17 (Fig. 5), the changes in the thicknesses of the second ferromagnetic layer A and the second ferromagnetic layer B had little effect on the exchange coupling energy J_k in the case of the
5 $\text{Co}_{90}\text{Fe}/\text{Fe}_{50}\text{Co}/\text{Co}_{90}\text{Fe}/\text{IrMn}$ -based exchange-coupled films.

[0062]

Furthermore, as seen from Examples 12-15 (Fig. 4) and Examples 18-21 (Fig. 5), these two types of exchange-coupled films demonstrated a slight increase of the exchange coupling
10 energy J_k with increase in the thickness of the first ferromagnetic layer but the increase rate was not so large.

[0063]

Subsequently, the spin valve film and thin film magnetic head MH1 according to an embodiment of the present invention
15 will be described with reference to Fig. 6. The thin film magnetic head MH1 is provided with a magnetic detecting device MD as a reproducing head and a magnetic field creating device RD as a recording head. The magnetic detecting device MD is comprised of nonmagnetic substrate 1, lower magnetic
20 shield layer 3, lower gap layer 5, spin valve film 47, electrode layer 45, hard magnetic layer 33, upper gap layer 39, upper magnetic shield layer 19, and so on.

[0064]

The nonmagnetic substrate 1 is made of a material of
25 Al_2O_3 -TiC or the like. The lower magnetic shield layer 3 is made of a soft magnetic material such as NiFe, sendust,

FeCo, FeCoNi, or the like and is deposited on the nonmagnetic substrate 1. The thickness of the lower magnetic shield layer 3 is set in the range of 0.5 μm to 4 μm .

[0065]

5 The lower gap layer 5 is made of a nonmagnetic insulator such as Al_2O_3 , AlN, SiO_2 , or the like and is deposited on the lower magnetic shield layer 3. The thickness of the lower gap layer 5 is set in the range of 5 nm to 30 nm.

[0066]

10 The spin valve film 47 is a GMR (Giant Magneto Resistive) element, and includes antiferromagnetic layer 7, ferromagnetic layer sandwich 41, nonmagnetic, conductive layer 25, and free layer 27, which are deposited in order on the lower gap layer 5.

15 [0067]

The antiferromagnetic layer 7 is similar to the antiferromagnetic layer 7 of the exchange-coupled film 100 according to the aforementioned embodiment, and is deposited on the lower gap layer 5.

20 [0068]

The ferromagnetic layer sandwich 41 consists of the following layers in order from the bottom: second ferromagnetic layer 11A containing a material of the face-centered cubic structure, first ferromagnetic layer 25 13 containing a material of the body-centered cubic structure, second ferromagnetic layer 11B containing a

material of the face-centered cubic structure, nonmagnetic intermediate layer 15, and third ferromagnetic layer 17, which are deposited in the order named on the antiferromagnetic layer 7.

5 [0069]

The second ferromagnetic layer 11A, first ferromagnetic layer 13, and second ferromagnetic layer 11B are similar to those of the exchange-coupled film 100 according to the aforementioned embodiment, and these three layers are referred to together as layer structure 9 herein.

[0070]

The nonmagnetic intermediate layer 15 is a nonmagnetic metal layer of Ru or the like and the third ferromagnetic layer 17 is a ferromagnetic material of FeCo or the like. The thickness of the nonmagnetic intermediate layer 15 is set in the range where the layer structure 9 can be antiferromagnetically exchange coupled with the third ferromagnetic layer 17; for example, it is set in the range of approximately 0.3 to 1.2 nm. The third ferromagnetic layer 17 is preferably made of the same material as the second ferromagnetic layers 11A, 11B and the thickness thereof is set to be approximately equal to that of the layer structure 9.

[0071]

25 Then the ferromagnetic layer sandwich 41 and the antiferromagnetic layer 7 form the exchange-coupled film

200.

[0072]

In the exchange-coupled film 200 of this configuration, as described previously, the direction of magnetization of the layer structure 9 is pinned along a certain direction (a direction perpendicular to the track width direction) by the exchange coupling field at the interface between the antiferromagnetic layer 7 and the second ferromagnetic layer 11A. Furthermore, the layer structure 9 is antiferromagnetically exchange coupled through the nonmagnetic intermediate layer 15 with the third ferromagnetic layer 17, so that the magnetization of the third ferromagnetic layer 17 is pinned in the direction opposite to the magnetization of the layer structure 9. Therefore, the magnetization of the ferromagnetic layer sandwich 41 is stably pinned in the predetermined direction by the antiferromagnetic layer 7.

[0073]

Since in the ferromagnetic layer sandwich 41 the layer structure 9 and the third ferromagnetic layer 17 are antiferromagnetically exchange coupled with each other through the nonmagnetic intermediate layer 15, the antiferromagnetic layer 7 demonstrates an effective increase of its force of pinning the direction of magnetization of the ferromagnetic layer sandwich 41, thus offering higher reliability. Since the magnetization is unlikely to leak

from the ferromagnetic layer sandwich 41, the reliability is further improved.

[0074]

The nonmagnetic, conductive layer 25 is made of an electrically conductive, nonmagnetic material such as Cu, Ru, Rh, Ir, Au, Ag, or the like and is deposited on the third ferromagnetic layer 17. The thickness of the nonmagnetic, conductive layer 25 is set in the range of 1 nm to 4 nm.

[0075]

The free layer 27 is made of a ferromagnetic material such as Fe, Co, Ni, NiFe, CoFe, CoZrNb, FeCoNi, or the like and is deposited on the nonmagnetic, conductive layer 25. The thickness of the free layer 27 is set in the range of 0.5 nm to 10 nm.

[0076]

Track part 27b being a central region of the free layer 27 functions as a portion in which the direction of magnetization is changed by the leakage field from the outside. The optical track width is set at the level of approximately 0.1 μ m.

[0077]

The hard magnetic layer 33 is placed so as to sandwich the spin valve film 47 from the both ends, and applies a bias magnetic field to the free layer 27.

[0078]

The hard magnetic layer 33 is made of a hard magnetic

material with high coercive force such as CoCrPt, CoPt, CoTa, or the like and the gap between hard magnetic layer regions 33, 33 is set at approximately 0.5 μ m at the narrowest position.

[0079]

5 An under layer 31 is formed below the hard magnetic layer 33, is made of a metal material such as TiW, Ta, CrTi, or the like, and is deposited over the side faces of the spin valve film 47 and over the lower gap layer 5. A protective layer 35 of Ta, Al₂O₃, or the like is formed on each hard
10 magnetic layer region 33. The under layer 31, hard magnetic layer 33, and protective layer 35 as described can be deposited after the deposition of the spin valve film 47 and subsequent patterning of the spin valve film 47 (applicable techniques include ion milling, RIE, etc.)..

15 [0080]

 A pair of electrode layers 45, 45 are placed apart from each other on the left and right of the track part 27b of the free layer 27 and are deposited over the protective layer 35 on the both sides. The electrode layers 45 are made, for
20 example, of an electroconductive material such as Au, Ag, or the like and supply an electric current (sense current) in parallel with the stack direction of the spin valve film 47 into the spin valve film 47.

[0081]

25 Namely, electrons supplied from one electrode layer 45 migrate in parallel with the film surface in the spin

valve film 47 to reach the other electrode layer 45. An electric current flows in the opposite direction to the migration of electrons. The spacing between the pair of electrode layers 45, 45 is set at about 0.1 μm at the narrowest position. The thin film magnetic head of this type is called a CIP (Current in Plane) type GMR head.

[0082]

A protective layer 37 is deposited on each electrode layer 45 and the protective layer 37 is made of Ta, Al_2O_3 , or the like.

[0083]

The upper gap layer 39 is made of a nonmagnetic insulator such as Al_2O_3 , AlN, SiO_2 , or the like and is deposited over the protective layer 37 and over the upper surface of the track part 27b of the free layer 27. The thickness of the upper gap layer 39 is set in the range of 5 nm to 30 nm.

[0084]

The upper magnetic shield layer 19 is made of a soft magnetic material such as NiFe, sendust, FeCo, FeCoNi, or the like and is deposited on the upper gap layer 39. The thickness of the upper magnetic shield layer 19 is set in the range of 0.5 μm to 4 μm . Since the magnetic shield layers 3, 19 each are made of the soft magnetic material, they prevent leakage fields except for the leakage field from the magnetization transition area as a detection target from entering the interior of the spin valve film 47.

[0085]

Next, the functions of the spin valve film 47 and the thin film magnetic head MH1 will be described. The track part 27b of the free layer 27 is kept in single domain structure in which the magnetization thereof is directed in the same track width direction as the magnetization of the hard magnetic layer 33, by the bias magnetic field created by the pair of hard magnetic layer regions 33, 33. Then the orientation of the magnetization in the track part 27b of the free layer 27 varies depending upon the leakage field from the magnetization transition area of the magnetic recording medium or the like, i.e., depending upon whether the magnetization transition area is pole N or pole S.

[0086]

Since the orientation of magnetization of the ferromagnetic layer sandwich 41 is pinned by the antiferromagnetic layer 7, the transmissibility of electrons (electric current) between the pair of electrode layers 45 varies depending upon a resistance change according to a cosine between magnetization directions of the track part of free layer 27 and the third ferromagnetic layer 17 in the ferromagnetic layer sandwich 41. This variation of electric current is detected to detect the leakage field from the magnetization transition area as a detection object of the magnetic recording medium. The magnetic field can be detected by detecting the voltage while keeping the

supplied current (sense current) constant, and it is common practice to employ the detection of this type.

[0087]

Since the present example adopts the exchange-coupled film 200 including the antiferromagnetic layer 7 and the layer structure 9, similar to the exchange-coupled film 100 of the aforementioned embodiment, for pinning the magnetization of the ferromagnetic layer sandwich 41 including the third ferromagnetic layer 17, the direction of magnetization of the ferromagnetic layer sandwich 41 including the third ferromagnetic layer 17 is pinned by sufficient exchange coupling energy while keeping the thickness of the antiferromagnetic layer 7 smaller than before.

[0088]

Since this permits the spin valve film 47 to be made thinner and also permits the gap to be made narrower between the upper magnetic shield layer 19 and the lower magnetic shield layer 3 of the thin film magnetic head MH1, it becomes feasible to achieve readout of the leakage field from the magnetic recording media in which information is recorded in higher density.

[0089]

Furthermore, since the thickness of the antiferromagnetic layer 7 can be made thinner than before, it is feasible to decrease the shunt ratio of the sense current

flowing in the antiferromagnetic layer 7 among the electric currents flowing in the spin valve film 47. This results in increasing the MR ratio and the amount of resistance change of the thin film magnetic head and thus enables implementation of higher output of the thin film magnetic head.

[0090]

Since the direction of magnetization of the ferromagnetic layer sandwich 41 is surely pinned even if the thickness of the antiferromagnetic layer 7 is made thinner than before as described above, it becomes feasible to implement stable readout operation in the spin valve film 47 and the thin film magnetic head MH1.

[0091]

Here some explanation will also be given about magnetic recording of data. The magnetic field creating device RD for writing magnetic data is mechanically coupled to and on the magnetic detecting device MD of the thin film magnetic head MH1. Data is written into the magnetization transition area of the magnetic recording medium by the leakage field from the magnetic field creating device RD.

[0092]

Thin film magnetic heads with the spin valve film as in the present embodiment were fabricated and evaluated as to the performance including the MR ratio and others.

[0093]

The MR devices formed as thin film magnetic heads

corresponding to the above embodiment had the basic configuration of NiCr (5 nm)/antiferromagnetic layer/magnetization pinned layer/Cu (1.9 nm)/CoFe (2.5 nm) (free layer)/Cu (3 nm)/Ta (2 nm). Numerals are based on the unit of nm. Here the ferromagnetic layer sandwich was of the synthetic structure consisting of the layer structure/Ru (0.8 nm)/Co₉₀Fe (1.6 nm).

[0094]

(Examples 22-24)

The configuration of antiferromagnetic layer/layer structure was IrMn₈₀ (5 nm)/Co₉₀Fe (0.5 nm)/Fe₉₅Ta/Co₉₀Fe (0.5 nm), as presented in the table of Fig. 7, and the thickness of Fe₉₅Ta as the layer of the body-centered cubic structure was 0.5, 0.7, or 0.9 nm in order of Examples 22-24.

[0095]

(Examples 25-27)

The configuration of antiferromagnetic layer/layer structure was IrMn₈₀ (5 nm)/Co₉₀Fe (0.5 nm)/Fe₅₀Co/Co₉₀Fe (0.5 nm) and the thickness of Fe₅₀Co as the layer of the body-centered cubic structure was 0.5, 0.7, or 0.9 nm in order.

[0096]

(Comparative Example 11)

The magnetic head was made in the same manner as in Example 22 except that the configuration of antiferromagnetic layer/layer structure was IrMn₈₀ (5 nm)/Co₉₀Fe (1.5 nm).

[0097]

(Comparative Example 12)

The magnetic head was made in the same manner as in Example 22 except that the configuration of antiferromagnetic layer/layer structure was PtMn (13 nm)/Co₉₀Fe (1.5 nm).

[0098]

The MR ratios and the amount of resistance change of these thin film magnetic heads are presented in Fig. 7.

[0099]

It is clearly seen from Examples 22-27 that the thin film magnetic heads with the spin valve film according to the present embodiment achieve the decrease in the film thickness of the antiferromagnetic layer without decrease of the exchange coupling energy, thus decrease the shunt ratio of the sense current flowing in the antiferromagnetic layer, and eventually increase the MR ratio and the amount of resistance change, as compared with Comparative Example 12 being the aforementioned conventional configuration.

[0100]

It is noted that the MR ratio can be increased by decreasing the film thickness of the antiferromagnetic layer even in the case of the spin valve film having the exchange-coupled film consisting of the disordered alloy and the conventional ferromagnetic layer sandwich different from the configuration in which the ferromagnetic layer of the face-centered cubic structure is placed between the

ferromagnetic layers of the body-centered cubic structure as seen in Comparative Example 13. However, it is difficult to put it into practical use, because the exchange coupling energy is low as previously described in Comparative Examples 1-4.

[0101]

The thin film magnetic head MH2 according to an embodiment of the present invention will be described below with reference to Fig. 8.

[0102]

The thin film magnetic head MH2 according to the present embodiment is different from the thin film magnetic head MH1 in that one electrode layer 45 is laid so as to be in electrical contact with the top surface of the spin valve film 47 and the other electrode layer 45 is laid so as to be in electrical contact with the bottom surface of the spin valve film 47 and in that the sense current flows in the stack direction of the spin valve film 47. The thin film magnetic head of this type is called a CPP (Current Perpendicular to Plane) type GMR head.

[0103]

In correspondence with this configuration, insulating layers 43, 43 of alumina or the like are formed, instead of the under layer 31 and protective layer 35, up and down on the hard magnetic layer 33 and between the electrode layers 45.

[0104]

Since the thin film magnetic head MH2 of the present embodiment adopts the spin valve film 47 capable of achieving the sufficient exchange coupling energy while making the thickness of the antiferromagnetic layer thinner as the
5 aforementioned thin film magnetic head MH1 did, it is feasible to narrow the gap between the upper magnetic shield layer 19 and the lower magnetic shield layer 3 without degradation of reliability and to substantialize the magnetic head of
10 narrow gap structure.

[0105]

In addition, the decrease in the thickness of the antiferromagnetic layer 7 leads to a decrease of the resistance in flow of the electric current flowing through
15 the antiferromagnetic layer 7 in the spin valve film 47, and this increases the MR ratio of the magnetic head.

[0106]

Next, the magnetic head apparatus and magnetic recording/reproducing apparatus with the aforementioned
20 thin film magnetic head MH1 or MH2 will be described below.

[0107]

Fig. 9 is a perspective view showing a hard disk apparatus (magnetic recording/reproducing apparatus) 201 according to an embodiment of the present invention. The
25 hard disk apparatus 201 is constructed so as to actuate a head arm assembly (HAA) (magnetic head apparatus) 215 and

record and reproduce magnetic information (magnetic signals) on a recording surface (upper surface in Fig. 9) of each hard disk (magnetic recording medium) 202 rotating at high speed, by thin film magnetic head 210.

5 [0108]

The head arm assembly 215 is comprised of gimbal (head supporting device) 212 carrying slider 211 with the aforementioned thin film magnetic head MH1 formed therein, and suspension arm 213 to which the gimbal is coupled, and
10 can be rotated about shaft 214, for example, by a voice coil motor. The thin film magnetic head MH1 may be replaced by MH2. As the head arm assembly 215 is rotated, the slider 211 moves in the radial direction of the hard disk 202, i.e., in the direction transverse to track lines.

15 [0109]

Fig. 10 is an enlarged perspective view of slider 211. The slider 211 is of approximately rectangular parallelepiped shape and the thin film magnetic head MH1 is formed on base 211a of AlTiC ($\text{Al}_2\text{O}_3 \cdot \text{TiC}$). The surface on this side in the
20 same figure is a surface facing a recording surface of hard disk 202 and is called an air bearing surface (ABS) S. As the hard disk 202 is rotated, the slider 211 comes to float by air flow caused by the rotation and the air bearing surface S is kept apart from the recording surface of the hard disk
25 202.

[0110]

Recording terminals 218a, 218b and reproducing terminals 219a, 219b are connected to the thin film magnetic head MH1 and the suspension arm 213 shown in Fig. 9 is provided with wires (not shown) for input/output of electric signals, which are connected to the respective terminals. Overcoat layer 221 indicated by dashed lines in the figure is provided for protecting the thin film magnetic head MH1. The air bearing surface S may be coated with a coating of DLC (Diamond Like Carbon) or the like.

[0111]

Since the head arm assembly 215 and hard disk apparatus 201 as described above use the foregoing thin film magnetic head MH1 or MH2, they present the operational effect similar to that described above.

[0112]

It is noted that the present invention is by no means intended to be limited to the above embodiments but can be modified in a variety of modification forms.

[0113]

For example, in the thin film magnetic heads MH1, MH2, the ferromagnetic layer sandwich 41 forming the exchange-coupled film 200 is of the so-called synthetic structure in which the layer structure 9 and the third ferromagnetic layer 17 are stacked through the nonmagnetic intermediate layer 15, but the ferromagnetic layer sandwich 41 can be comprised of only the layer structure 9.

[0114]

The thin film magnetic head MH2 may be constructed as a TMR head in which the nonmagnetic, conductive layer 25 is replaced by an insulating layer of alumina or the like.

5 [0115]

The exchange-coupled film and spin valve film according to the embodiment of the invention can also be applied to MRAM (magnetic random access memory) or the like.

[0116]

10 [Effects of the Invention]

As described above, the present invention has provided the exchange-coupled film that can be made thinner than before and that yields the sufficient exchange coupling energy, the spin valve film using it, the thin film magnetic head, the magnetic head apparatus, and the magnetic recording/reproducing apparatus. This permits implementation of higher density in the hard disk apparatus and others.

[Brief Description of the Drawings]

20 [Fig. 1]

Fig. 1 is a schematic illustration showing a sectional structure of an exchange-coupled film according to an embodiment of the present invention.

[Fig. 2]

25 Fig. 2 is a table showing compositions and characteristics of exchange-coupled films in Examples 1-8,

Comparative Examples 1-10, and Reference Example 1.

[Fig. 3]

Fig. 3 is a drawing showing a typical example of magnetization curves in the direction of the magnetization easy axis of the exchange-coupled films in Examples 1-8.

[Fig. 4]

Fig. 4 is a table showing compositions and characteristics of exchange-coupled films in Example 1 and Examples 9-15.

[Fig. 5]

Fig. 5 is a table showing compositions and characteristics of exchange-coupled films in Example 8 and Examples 16-21.

[Fig. 6]

Fig. 6 is a schematic illustration showing a sectional structure of a thin film magnetic head according to an embodiment of the present invention.

[Fig. 7]

Fig. 7 is a drawing showing film compositions and characteristics of thin film magnetic heads in Examples 22-27 and Comparative Examples 11 and 12.

[Fig. 8]

Fig. 8 is a schematic illustration showing a sectional structure of another thin film magnetic head according to an embodiment of the present invention.

[Fig. 9]

Fig. 9 is a perspective view showing a hard disk device according to an embodiment of the present invention.

[Fig. 10]

Fig. 10 is an enlarged perspective view of a slider
5 of Fig. 9.

[Explanation of Reference Numerals]

3:lower magnetic shield layer (shield layer)

7:antiferromagnetic layer

11A, 11B:second ferromagnetic layer

10 13:first ferromagnetic layer

15:nonmagnetic intermediate layer

17:third ferromagnetic layer

19:upper magnetic shield layer (shield layer)

25:nonmagnetic conductive layer

15 27:free layer

41:ferromagnetic layer sandwich

45:electrode layer

47:spin valve film

100,200:exchange-coupled film

20 201:hard disk apparatus (magnetic recording/reproducing apparatus)

215:head arm assembly (magnetic head apparatus)

MH1,MH2:thin film magnetic head

[Document Name] ABSTRACT

[Abstract]

[Problem] To provide an exchange-coupled film that can be made thinner than before and that yields sufficient exchange coupling energy, a spin valve film using it, a thin film magnetic head, a magnetic head apparatus, and a magnetic recording/reproducing apparatus.

[Means of Solution] An exchange-coupled film having a ferromagnetic layer sandwich 41 comprising a first ferromagnetic layer 13 containing a ferromagnetic material of the body-centered cubic structure and a pair of second ferromagnetic layers 11A, 11B containing a ferromagnetic material of the face-centered cubic structure and formed on respective sides of the first ferromagnetic layer; and an antiferromagnetic layer 7 containing a disordered alloy and formed on one of the second ferromagnetic layers, is provided. It yields sufficient exchange coupling energy even in smaller thickness of the antiferromagnetic layer 7 than before, whereby it becomes feasible to decrease the thickness of the exchange-coupled film 100.

[Selected Drawing] Fig. 1